June 1999 • NREL/SR-520-26154

Subcontractor Report

Development of a Modular, Bi-Directional Power Inverter for Photovoltaic Applications

Final Report
August 1995 — March 1998

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Trace Engineering Company, Inc.
Arlington, Washington

NREL

National Renewable Energy Laboratory

1617 Cole Boulevard
Golden, Colorado 80401-3393

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Prepared under Subcontract No. ZAF-4-14271-08

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FINAL REPORT

PVMaT Subcontract: RAF-4-14271-00

Subcontractor: Trace Engineering Company, Inc.

Subcontract Title: Modular, Bi-Directional Power Inverter for Photovoltaic Applications

Reporting Period: August 1995 to March 1998

1.0 SUMMARY

The goal of this research and development contract was to develop and prototype for manufacturing a modular, bi-directional power inverter for photovoltaic applications. This modular inverter will be used as a building block for larger inverters by connecting in parallel (for higher power) or in series (for higher AC voltage) or both. The modular inverter will be capable of being interconnected for single, split and three phase configurations for both 60 Hertz (domestic) and 50 Hertz (international) applications. The design will also allow construction of units with different DC input voltages and AC output voltages to further satisfy various application and market requirements.

By standardizing on a single “building block” inverter module, the need to build multiple models and sizes for different applications can be avoided. The higher volume of a single design will allow improved manufacturing and will result in higher reliability by reducing low volume modifications. The result will be lower cost and improved performance of photovoltaic systems.

Achievements

During **Phase I** (August 1995 to August 1996) of this research and development effort, Trace Engineering made the following achievements towards completing the goals of this contract:

- Conducted a review of possible inverter designs and identified preferable approaches.
- Developed and built initial “breadboard” prototypes of two different inverter designs.
- Evaluated the performance through computer modeling and laboratory testing.
- Selected one of the two designs for further development into a manufacturable prototype.
- Refined the design to reduce no load power consumption. Reduced the consumption from 30 watts to less than 10 watts for a 2kW power inverter module.
- Developed an advanced hardware based protection system for the MOSFET transistors “H” bridges to improve reliability.
- Built a manufacturable prototype of the selected design using production methods and materials. The prototype was built up in an existing product chassis to emphasize the compatibility of the design with current production methods and components.
- Demonstrated the final Phase I prototype to the PVMaT subcontract monitors Holly Thomas, Ward Bower and Ben Kroposki at the annual review meeting held at Trace Engineering in August of 1996. It was also submitted to Sandia National Laboratories for additional testing.

During **Phase II** (September 1996 to March 1998) of this research and development effort, Trace Engineering made the following achievements towards completion of the goals of this contract:

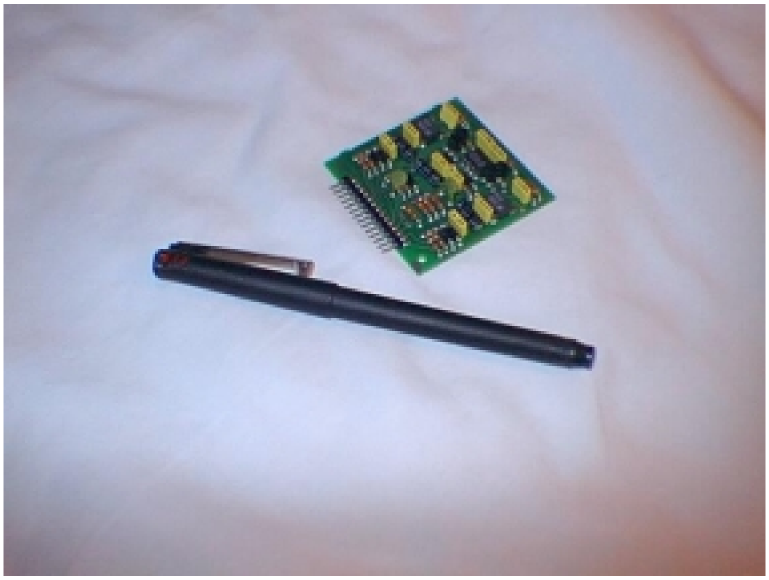
- Developed control and protection systems required to enable the operation of inverters in series, parallel and three phase configurations. The system developed includes both hardware and software components to coordinate the operation of the inverters and split the loads being powered.
- Successfully fielded paralleled inverter/charger systems utilizing the developed control and protection systems in over 20 applications in the US, Australia, Indonesia, South America, Spain and other countries. One installed system included four inverters in a parallel/series configuration for 22 kW of continuous power at 120/240 VAC.
- Developed advanced software control systems to maximize the system performance and to allow redundant operation. The resulting advanced control system simplified the intercommunication system required between the inverters to improve reliability and provide fault tolerance and improve ease of trouble shooting in the field.
- Developed, prototyped and demonstrated a modular inverter packaging system which incorporates multiple inverters and the required balance of systems components for a complete application.
- Introduced the Power Module Enclosure System to our distributors for individual and multiple inverter installations based on the prototype developed under this subcontract. This product incorporates the inverter and the balance of systems components (cables, breakers, controllers, metering etc.) into a single outdoor, bug proof metal enclosure. The Power Module enclosure system was submitted to Underwriters Laboratories for listing under the UL1741 Photovoltaic Inverter System standard. The Power Module enclosure system was UL listed in March of 1998.
- Developed, prototyped and have planned for production a reduced cost 2.5-kW version of our SW series for use as a modular inverter. The cost reduction were based on ideas developed in the research of other inverter topologies and designs. The first production of this 2.5-kW platform will occur in Q1 of 1999.

  A cost reduction of 35% for parts and 42% for labor was achieved compared to the existing 2.5-kW sinewave inverter product’s parts and labor content.

Improvements directly attributable to this PVMaT subcontract

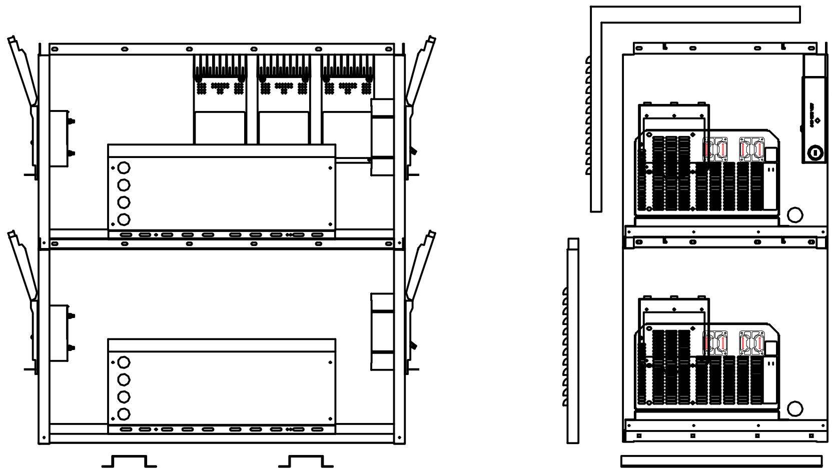
This research and development contract has resulted in several benefits for Trace Engineering and the PV industry directly attributable to the PVMaT program:

- Application of the hardware based protection circuit developed in Phase I was completed on Trace's existing DR and SW series product lines. This additional protection circuit was phased into full production starting in April of 1997. This improvement resulted in a substantial improvement in factory yields and a very significant reduction of field failures – a drop of as much as 80% on some product models.

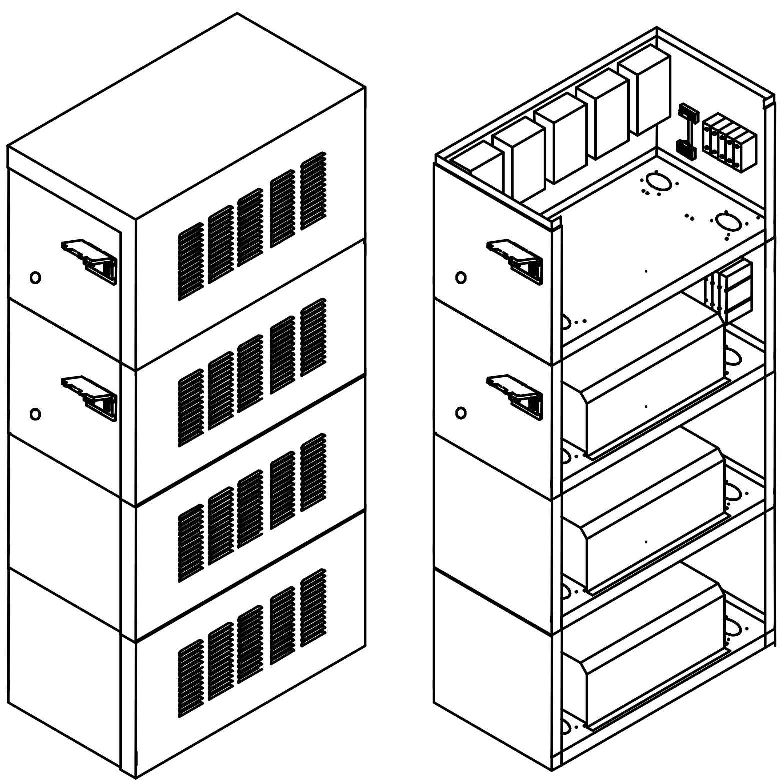


Additional Protection Circuit Added to Production Designs

- Accelerated development and introduction of the Power Module enclosure/balance of systems package produced a product that is the most advanced balance-of-system hardware package available in the world. This product is a big step towards the standardization of system and equipment design for Trace's customers.



Power Module Enclosure System with Dual SW series Inverters and PV Controllers



Power Module Enclosure System for a Three Phase Application

- Development of the cost reduced 2.5-kW modular inverter based on the current SW series software and topology. This new inverter/charger uses many new construction and manufacturing methods to reduce cost by 40% , simplify production, decreased parts count by over 20%, reduce labor required by 30% , and increase the flexibility in the manufacturing process. It will enter production in the first quarter of 1999 as the Trace Engineering PS series inverter/charger.

2.0 INTRODUCTION

This final report covers both Phase I and Phase II of the research and development of a better, more manufacturable modular, bi-directional power inverter for photovoltaic applications by Trace Engineering Company, Inc. of Arlington, Washington. This work has been conducted under the PVMaT Phase 4A1 program. The contract period started in August of 1996 and was finished in March of 1998.

Trace Engineering has been manufacturing power inverters for over 13 years and has built more than 300,000 inverters. The majority of the inverters built have been used in renewable energy applications. Traditionally, Trace concentrated on the stand-alone, non-utility interactive applications. With the introduction of the Trace SW series in 1994, Trace expanded its product line into utility interactive and larger hybrid system applications. Trace Engineering is now the largest manufacturer of inverters for renewable energy applications in the world.

The increased production volume and expansion of the Trace product line into numerous models and power levels to meet the requirements of the wide range of possible applications has caused Trace to see the need for the development of new inverter designs which could be manufactured more easily. The new design also needs to provide more flexibly in different applications and achieve higher performance and reliability. This PVMaT subcontract has provided the needed impetus to accelerate those efforts through the development of a modular, bi-directional power inverter which could be used as a “building block” for larger and more complex systems. The modular inverter is expected to fill the requirements for stand-alone, hybrid and utility-interactive applications by connecting them in parallel (for higher power), in series (for higher AC voltages) and in single-phase, split-phase and three-phase configurations.

3.0 OBJECTIVES

The overall objective of this contract was to “Develop and prototype for manufacturing a modular DC to AC power inverter for photovoltaic applications”. The specific goals of this contract were:

- Achieve a significant cost reduction compared to current technologies
- Increase modularity of the inverter system to allow easier expandability and improved servicing by the use of multiple inverter modules connected in series, parallel and/or three phase configurations.
- Attain higher efficiency through better inverter load matching
- Increased power density to reduce size of the inverter module
- Expand the ability to allow one hardware design & software “core” to be used by multiple market segments to increase production volume and manufacturing economies.
- Improved reliability of photovoltaic systems through the application of N+1 redundant system design through the use of modular inverters.
- Increased adaptability of the inverter system design to meet unknown application requirements in new and emerging inverter applications.

Phase I objectives were mostly aimed at the development of the modular inverter itself, while Phase II handled further development of the modular inverter system including packaging systems, balance of systems components, fault tolerance, protection and control to allow use of multiple inverters as a group for higher power applications.

4.0 SCOPE OF WORK

The research and development work completed under this contract was involved in the following areas of effort. Effort made on each of the work areas is summarized along with the results.

4.1. Reduced cost over existing technologies

Reduction of cost was a major goal in this contract. Cost reductions were achieved through the following activities:

- Evaluation of various inverter topologies and construction was completed. After developing designs utilizing high frequency and high/low frequency conversion methods in Phase I, we returned to our currently manufactured SW series inverter/charger to complete Phase II. The work in Phase II of this contract resulted in the development of a lower cost 2.5-kW modular inverter/charger based on the SW series topology but with 35% lower parts cost and 42% less assembly/test labor cost required compared to the existing 2.5-kW SW series product.
- Investigation of the relationship of the inverter to the balance of systems components required to achieve the lowest overall cost and maximum performance was completed. This resulted in the development of the Power Module enclosure system which is designed to incorporate a modular inverter and all of the required balance of systems components into a single enclosure. By standardizing the system design and eliminating custom engineering and fabrication, the overall system cost is reduced while system flexibility and adaptability is maximized.
- Development of a multi-market inverter platform which can be configured to meet a wide variety of applications, increasing the manufacturing volume and economies was completed in the design of the lower cost SW series based product. By eliminating standard features and making them optional instead, the new 2.5-kW product has a lower cost but can be customized to meet a specific market requirements and price goals.
- Development and demonstration of the modular inverter control and protection systems was completed using the existing SW series inverter/charger. The modular inverter concept reduces overall system costs by eliminating the need to oversize a system for future growth/expansion. It also allows matching of the inverter more closely to the load than previously possible.

The immediate result of this contract is the development of two products which will reduce system cost. The new 2.5-kW inverter /charger series is expected to be 40% lower at the retail level than the 2.5-kW SW series inverter currently offered.

The Power Module enclosure system's cost reduction are harder to estimate since the product has little else to compare with. Reductions are achieved at several levels – reduced engineering, fabrication, transportation, installation and servicing costs all add up to a significant level in many system designer's opinions.

Trace will continue developing other inverter topologies with the major goal of achieving lower cost. The decision to bring a cost reduced version of the existing SW series to market in the immediate time frame was based on the positive results achieved during the Phase II portion of this contract. It also is being pursued because of the lower investment requirements and quicker time to market by developing a new product from a product platform currently in production with over 25,000 units shipped.

4.2. Improved power density

Both the Phase I and Phase II inverter designs achieved a higher power density compared to current product designs. With the new 2.5-kW inverter/charger that is entering production, the overall volume was reduced 33% compared to the previous 2.5-kW unit. On a per kW basis, the power density is comparable to Trace's highest power density unit, the SW5548 inverter.

4.3. Modularity to allow easier expandability and adaptability

The new 2.5-kW inverter/charger module has been designed from the start to allow use in either parallel or series combinations to meet a wide variety of capacity and system configuration requirements. It uses the exact same control and protection system of the larger SW series inverter/charger. The same intercommunication methods are utilized to series and parallel the new inverter modules and in fact, the existing SW series can also be used as an inverter module in the same way using the same method and hardware. This achievement was not originally anticipated due to the complexity of the control and protection systems required. By simplifying the systems once developed, application to the existing platforms was made possible.

The design of the new 2.5-kW inverter/charger includes many features to increase the flexibility of the manufacturing process. The control board of the new 2.5-kW platform is retrofittable to the old SW series platform – Only one control board needs to be manufactured. The new control board is also designed for machine stuffing and soldering – reducing cost and improving quality. The new control board is 34% smaller and has an improved layout using four layer construction to reduce size and eliminate emissions and interference problems. Its design has been tested to the FCC and CE requirements by UL at the Camas, WA facility. We will be using this new circuit board on all sinewave inverters by the first quarter of 1999.

The software and hardware developed to allow connection of multiple inverters is being designed into the standard software for both of the inverter platforms. No special versions will be required to series, parallel, series-parallel or connect in three phase – only some additional relatively low cost hardware is required. This maximizes the expandability, adaptability and flexibility of the system enormously.

The elimination of custom versions for special applications and the incorporation of the additional product features as plug in assemblies improves the serviceability of the product compared to the previous SW series design which required special versions and had all of the features standard.

4.4. Improved efficiency

The efficiency of the modular inverter approach has been maximized by work completed both in Phase I and in Phase II of the contract.

The work completed in Phase I of the contract demonstrated that the High/Low frequency conversion approach could be used to achieve a high efficiency inverter design – even at low load levels. The development of the additional circuit that reduced the no load consumption while maintaining full output without the cost and complexity of a co-inverter was a significant development.

The efficiency of the modular inverter system was the focus of the work completed in Phase II of the contract. The reduction of the circulating currents produced by the connection of two bi-directional inverters in parallel was a major area of effort in achieving the highest efficiency. In the end, the problem of circulating currents was totally eliminated by the combination of software control and a hardware component.

The 2.5-kW inverter module developed in Phase II is based on the current production SW series. It includes the same design feature of low idle power consumption. This results in good low-power efficiency while maintaining good mid- and high-power efficiency by the use of the same conversion topology in both platforms.

The method used to parallel the modular inverters eliminated the need to turn off individual inverter modules when operating at low power levels since the power consumption of the multiple inverters were reduced to such a very low power level and all the circulating current between the individual inverters was eliminated. This reduces complexity of the inverter modules and the entire system, improving system reliability and fault tolerance.

4.5. Improved reliability

Improved reliability was the second major goal of this contract. Much work was completed in this area both in Phase I and II of the contract.

An electronic overcurrent protection system was developed and tested successfully on the 2-kW high/low frequency conversion inverter module during Phase I of this contract and was then adapted to the existing SW and DR series product lines. This “spin-off” made an enormous improvement in the product reliability of Trace’s main two products. This improved reliability was a direct result of this research and development contract’s work. The new 2.5-kW modular inverter includes this protective circuit as well.

The modular inverter approach developed also allows redundancy in the inverter system by allowing use of one more inverter module than required for the load. If a problem occurs with one of the inverter modules in the inverter system, the faulted inverter module can be shut off and even be removed without disrupting the inverter system or loads. This is often referred to as “N + 1” redundancy and is common in the telecommunication and computer industry for DC power supplies. This feature has been offered on some inverters by other companies, but never at a competitive price or in a bi-directional inverter/charger type product.

This redundancy and the ability to “hot swap” (change a modular inverter without shutting down the system) the modular inverters during operation are features that have been developed as part of both the control and protection systems development and the Power Module enclosure system development under Phase II of this contract.

The most promising product to come out of this development is a kit to allow connection of two inverter/chargers in parallel. This has high demand based on customer surveys. Additional versions (including the N+1 version) will depend upon the development of a customer base.

4.6. Expandability to other market segments

Trace’s modular inverter concept increases the ability of one product to meet the demands for a variety of market segments by being able to better match the power level, output configuration and redundancy requirements of the application.

The new 2.5-kW inverter/charger developed under Phase II of the contract also allows expansion into other market segments by the design of the modular inverter allows the additional features as plug-in assemblies to meet the application’s requirements and cost goals. The display, control relays, generator management and communications features are all optional instead of being standard as on the original SW series offered by Trace.

The Power enclosure system was also developed to allow the modular inverter system to serve other applications. New enclosures were designed to allow indoor or outdoor use. The number of allowable breakers and other components has been maximized to increase design flexibility. The enclosures themselves are designed to allow stacking up to four high to be flexible and to minimize use of floor space.

The potential for both the modular inverter system and the Power Module enclosure system in non-PV applications is very good. We are seeing a lot of interest from the commercial and large residential utility back-up market segment for use in place of fuel powered generator systems.

4.7. Increased adaptability to unknown application requirements

This is an area that both the modular inverter and the Power Module enclosure system excel – No known commercially available product is as adaptable to new and unforeseen requirements.

The modular inverter approach allows the system to be expanded as power requirements grow. The configuration of the system can also be changed easily – it can go from single phase to three phase without replacement or modification of the inverter modules. Only some additional hardware is required for the three phase application.

The Power Module enclosure system themselves are extremely adaptable to any application requirements – It is the nature of their design. Even non-Trace supplied hardware is easily accommodated.

TASKS - PHASE I

Work on Phase I of this contract was started in August of 1995 and was completed in August of 1996.

TASK 1 - INVERTER TOPOLOGY DESIGN AND VERIFICATION

Subtask 1.1 - Selection of topology

The development process of the inverter module involved several starts, stops and detours. Two separate inverter designs were considered and completed to the working prototype level.

1. The original design was based on a pure high frequency topology. This design was prototyped and successfully tested to power loads up to 1 kW. The design was abandoned for several reasons. The most significant problem was excessively high no load or idle power consumption. The 1-kW prototype required over 20 watts of DC power to produce an AC output. This is almost four times our design goal. Another problem was it required expensive design features and components to allow intermittent operation at high “surge” power levels required to start motors.
2. The development effort was then concentrated on a mixed high and low (hybrid) frequency topology - which uses a high frequency power transistor bridge and a low frequency transformer. This design has been used by several manufacturers but other designs inherently have suffered from high idle-power draw that is more than twice our design goals at the 2.5-kW power level.

The original high/low frequency inverter design was developed, built and tested by the primary project engineer, Roger Rosenbaum. Trace then hired another experienced engineer, Milt Rice, to assist Roger with the refinement of his approach. With the switch to the hybrid inverter topology, Milt became the primary project engineer and Roger was reassigned to other projects since Milt was much more experienced with the hybrid topology and Roger was needed for other projects. Roger continued to be involved for much of the testing portions of the project.

Subtask 1.2 - Design initial prototype and estimate operating limitations

Several initial prototypes were constructed and used to determine operating limitations. The transformer characteristics were developed from testing completed on these initial prototypes. Both the high frequency and the high & low frequency hybrid inverters were prototyped initially to the level of operating at several hundred watts.

The power testing of the original high frequency prototype resulted in the discovery of the final flaw in the design which caused us to switch to the hybrid topology. When the high frequency topology is developed to be bi-directional, the protection required to prevent failure of the inverter was found to be very difficult and is expensive to implement. This is further compounded once the inverter is required to allow high power intermittent operation. This problem resulted in changing the modular inverter development effort to the simpler hybrid topology.

The output stage of the high frequency topology was further developed into a new type of inverter product. The circuit was modified to allow AC as the input instead of DC. The AC is rectified into high voltage DC and the inverted back into DC power with the output stage of the high frequency inverter. This allow use of sensitive electronics on poor quality AC sources such as generators, modified square wave inverters and utility grids in developing countries.

This new product has been named the “CO-sine” inverter and was demonstrated at the SOLTECH 96 conference in Palm Springs, California in April of 1996. Twenty-five BETA units have been manufactured and have been sent out to various companies for testing and evaluation. This product is a direct off-shoot of this contract development effort and was expected to be potentially a significant seller. The loss of Milt Rice in an airplane accident caused us to put this product on hold until further engineering resources become available.

In the time period between the completion of the contract proposal and the award, some of the items listed to be developed in the contract for this subtask had already been developed, implemented, and fielded in the SW series inverter product. Most of these requirements (ground fault protection, anti-islanding, battery-less operation and maximum power point tracking for example) are included in the new version of the SW series inverter that is designed specifically for utility interactive applications. The methods developed and components used to meet these requirements were evaluated and determined to be compatible with the hybrid topology selected for the 2.5-kW inverter module.

Because these requirements were well developed and are known to present no obstacles for the new modular inverter design, they were considered in the design but not implemented at this point in the development process. They were included as in the Phase II portion of the contract as part of the final prototype development.

Some of the features have also been determined to be worth implementing on Trace’s currently manufactured SW series inverter design. Several features have been tested by another Trace engineer, Greg Thomas, using the SW series inverter as a test and development bed. This allowed faster development and enabled the SW series inverter to be used in the immediate future as a modular inverter in a wider variety of applications. The features allowed operation in parallel (for larger single phase systems) and in three-phase configurations for large more complex power systems.

Subtask 1.3 - Build prototype of Inverter

A first complete prototype of the hybrid topology inverter core was constructed in April of 1996 by Milt Rice. The prototype was designed to fit into an existing inverter chassis used in our DR series of modified square wave inverters. This was done to reduce the development time and cost by eliminating the need for mechanical engineering and prototype drawings at this early stage. The final chassis design would be selected once the working prototypes were further developed and fully tested. Use of an existing chassis also allowed us to assemble the inverter with existing fixtures and production equipment. This is very useful during a BETA test cycle since many changes may still occur in the design after the initial field testing.

Subtask 1.4 - Test Prototype / Demonstrate

The prototype of the 2-kW inverter module was tested and demonstrated to the engineering group at Trace Engineering's research and development laboratory. The bi-directional ability was demonstrated using manual control of the inverter's waveform in a process similar to method used by the existing SW series inverter. Since the intent of the modular inverter development is to utilize as much of the existing control software of the SW series inverter already developed. This was especially true of the utility interactive and battery charging software since the initial hybrid inverter prototype did not have enough code space to include all of the SW series inverter's control software, only manually controlled utility interactive and battery charging ability was demonstrated at this point. This manual control was achieved by incorporating a potentiometer into the circuitry which varied the output voltage of the inverter, allowing the amplitude modulation system control used by the SW series to be simulated.

TASK 2 - PERFORMANCE OPTIMIZATION

Subtask 2.1 - Analysis of prototype's performance

Operation as a stand-alone inverter was the initial development focus, since stand-alone operation presents some of the greatest technical challenges. Operation of inductive and capacitive loads was completed to help develop the protection and control systems. The prototype operated a wide variety of AC loads including resistive (heaters and light bulbs), motors (tools and an air compressor) and capacitive loads (power supplies and computers).

The output waveforms total harmonic distortion (THD) was monitored during the tests using a FLUKE 41B power meter system. The AC output voltage THD was found to range from 1% to 3 % for resistive loads and was less than 5% when operating inductive or capacitive loads.

The inverter was further developed to enable startup of a 3/4 horsepower air compressor by utilizing and advanced current limiting scheme which "soft started" the load by limiting the current being delivered to the motor. The high-frequency switching pulse width modulation of the inverter system was controlled to allow limitation of the AC output current to a safe level. This level was varied by both the duration of the overcurrent condition and the temperature of the MOSFET transistors. A software based programmable system was developed to allow customization of the current limit system to different MOSFET transistors or to provide different control routines.

Subtask 2.2 - Identify and prioritize problem areas to be addressed

The area requiring the greatest engineering attention involved improving the idle power consumption of the hybrid modular inverter design when AC loads are small or when there are no AC loads. Minimizing the idle power consumption is critical for small stand-alone applications since it significantly influences the efficiency curve below 50 % of the inverter's rating.

Several circuit designs were tested to reduce the idle power consumption without adding excessive cost to the inverter. Methods such as co-inverters and multiple transformers were built and tested.

One method was found to be very successful - it reduced the idle power consumption of the hybrid modular inverter from approximately 30 watts to under 10 watts. This approach was simple and very low cost. It also can be easily eliminated either at the manufacturing or installation levels for applications which do not require low idle power consumption. This design change improves the flexibility of the modular inverter for use with a wider range of market segments and lowers cost for use with a wider range of market segments.

Another important priority for the optimization of the hybrid modular inverter design was to improve the high power efficiency of the modular inverter. This optimization and development process in the Phase I effort was based solely on 12 volt DC inverter since the low voltage inverters always have a lower efficiency due to the very high DC current that has to be processed. To further optimize the inverter, higher DC voltage versions of the inverter design would need to be built and tested to determine the best ways to improve efficiency overall. Due to the limited development time, the higher DC input voltage versions were given a lower priority and the 12 volt DC version was the focus of this research and development.

The inverter protection and active current limiting system was also identified as needing further development and testing to ensure that the maximum reliability and performance was being achieved. The protection and active current limitation system were developed under Task 2.3 of the contract.

Subtask 2.3 - Develop a plan for addressing problem areas

A plan for the improvement of the idle power consumption was developed and then implemented. Many variants of the same idle reduction circuit design were tested in order to find the best method of reducing the power consumption. After approximately twenty different configurations were tested over a period of a few weeks, one method was found to reduce the idle power consumption from about 30 watts to about 12 watts. This level was the maximum amount we had hoped to achieve when we started (the SW series is considered to have a very low idle with a draw of 16 watts for 4-kW inverter).

Further testing and optimization of the method developed resulted in the reduction of the 12 watts of idle power consumption to under 8 watts with no additional hardware cost. This low consumption level was an unexpected result in this development and is even extremely low for commercially available non-sinewave inverters.

Further analysis of the inverter's design suggests that possibly another 2 watts may be eliminated by completing a minor redesign of the inverter's control board power supply circuitry.

The inverter protection and active current limit system were also further developed and refined. The motor starting ability was optimized during this development to allow the highest performance to be achieved without over stressing of the inverter. Further testing of the design at the production level will be required to ensure that manufacturing variability does not cause slight changes that would result in transistor damage or loss of inverter performance.

The same protection approach used in the 2-kW inverter module was also developed for the SW series and tested. The SW series inverter has the additional complexity of having three power sections. The protection circuitry for the SW series was developed on a plug-in daughter card to allow calibration outside the inverter to guarantee the protection and performance levels. This circuit was tested and demonstrated to be of significant value for that product. The further development of this circuit for the SW series was given to Greg Thomas to be completed outside the scope of this contract.

TASKS - PHASE II

Work on Phase II of this contract was started in September of 1996 and was completed in March of 1998.

TASK 3 - DEVELOPMENT OF CONTROL AND PROTECTION SYSTEMS

Subtask 3.1 - Define and detail requirements for control and protection

The work of defining the control and protection requirements was completed by Greg Thomas and Christopher Freitas. The goal of the design was to end up with one version of the inverter software for all applications – single, parallel, split-phase (120/240 VAC) or three-phase. As the complexity of the modular inverter based system increased, so did the requirement for additional components. This allowed the single and dual inverter applications to be offered at a lower price since less hardware is required.

The existing Trace SW series includes a “stacking” port which allows two inverters to be connected in series (on the AC side) to provide split-phase type power. Although this is useful in North America, few other countries have this type power. Most international customers want 230 VAC 50 Hz power either single- or three-phase.

The decision was made to utilize the existing SW series inverter/charger as a development platform for the parallel system. This initially appeared to be a challenge since the product was not originally developed to operate in parallel with other inverters. Further research and development, along with testing, found that the SW series was very suitable to parallel operation.

A goal for the development of the control and protection systems was to have a system that was simpler and more robust than the system used currently by the SW series for series operation. Experience with the current system had emphasized that simpler is better and that the ability to troubleshoot and allow partial operation when a failure occurs is critical for the success of the modular inverter concept.

Several ideas were developed for the modular inverter concept. The major ideas are summarized here:

- Master / Slaving of the inverter modules was limited to the clocking signal used to synchronize the output of the inverters and to a signal used to transfer to / from an AC source. All other aspects of the inverter’s operation are controlled individually by each inverter itself. This improves the reliability and allows operation as a N+1 redundant system.

- The detection of a phase loss on three phase and split phase (120/240 VAC) systems was left to an off-the-shelf external product. This improved reliability of the system and allowed operation of single phase loads when a problem occurs, while protecting the three phase or 240 VAC loads from damage.
- Two way communication from one inverter to another was avoided. The approach used is a circular pattern – the first inverter talks to the second, which talks to the third. This improves the tolerance of the system to partial failures – some of the inverters only need to talk, while others only have to listen. If a partial failure of the stacking port occurs (partial is typical) then the inverters location in the communication system can be re-arranged, allowing the system to fully operate.
- The system which coordinates the sharing of the inverter's output and prevents fighting when lightly loaded would be simple and not require high speed intercommunication. This was sought since the reliability and robustness of the modular inverter system is extremely important. Complex approaches simply were determined to be not acceptable.
- The software required to enable use of an inverter as a modular inverter would also allow use as a single inverter. With the SW series based system, the software would be standard in all production units. The three phase and parallel systems would use the standard software and not some specially developed software version. This approach makes the availability of replacement units and parts much less of an issue, and it simplifies the manufacturing, ordering and procurement of components.

The operation of the modular inverters involves many additional details which are covered in greater detail in the report (D 2.10) delivered at the Final Review Meeting on the Control and Protection System developed under this contract.

Subtask 3.2 - Develop hardware requirements

The development of the hardware required for the operation of the inverters as modules was completed as the design progressed. Hardware developed included the communication cables protection devices for DC side faults and phase loss on the AC output, and hardware to prevent the fighting of the inverters when lightly loaded.

Subtask 3.3 - Develop software requirements

The development of the software to control the operation of the modular inverters was completed. Several software solutions to the problem of the inverters fighting when lightly loaded were attempted. Each of the solutions developed was involved and increased the complexity of the system. Finally, a hardware solution was developed to prevent the fighting, allowing the software to be much simpler and more reliable.

The solution developed for the control of the modular inverters could be implemented with any inverter topology or design.

Subtask 3.4 - Select devices to meet required performance criteria

All of the components needed for the control and protection of the modular inverters was fabricated by Trace Engineering except for the phase loss detector for split- and three-phase applications. With the exception of the interconnecting cables, the devices fabricated and sourced are compatible with any Trace inverter topology or design.

Subtask 3.5 - Prototype control and safety systems

The control and safety systems were prototyped and tested. The DC side protection circuit was made standard on all SW and DR series inverters to improve the reliability of the products.

Five prototype modular inverter systems were shipped in October of 1997 for real world customer sited applications. They all operated successfully.

Subtask 3.6 - Test parallel and series ability and performance

The control and protection systems developed were tested in series, parallel and three phase configurations.

Five prototype modular inverter systems shipped in October of 1997 for real-world customer sited applications. All operated successfully.

Subtask 3.7 - Refine systems and repeat testing

The control and protections systems were further developed as the testing identified issues. Some additional hardware was provided to the sites in order to ensure acceptable operation under fault conditions and to allow the automatic resetting of the system when a fault condition occurred.

Subtask 3.8 - Complete report on performance achieved and identify what areas need to be addressed further

This report was provided as part of the Final Review Meeting held at NREL on June 25, 1998. (D-2.9)

The report described the current system used and the limitations it includes. A description of the system requirements was provided. Also detailed were the changes needed to improve the operation of this multiple inverter system

The primary improvements required are as follows:

- Better co-ordination of the multiple inverters connection to and from an AC source. This is especially true of inverters used with fuel powered generators.
- Expanded communication capability to the multiple inverters to allow monitoring and setup from a central display.

TASK 4 - PACKAGING

Subtask 4.1 - Define packaging requirements

This task was completed by Bill Hoffer during the period of January to March of 1997.

A report was delivered as part of the Final Review Meeting held at NREL on June 25, 1998. (D-2.8)

Subtask 4.2 - Investigate other industry designs

This task was completed in January of 1997. The result was the decision to build a custom enclosure instead of using existing 19”rack mount systems. This is due to the greater requirement for handling heavy weight items (such as batteries, inverters and transformers) and the use of large diameter cables. The 19” rack mount type systems are also designed for equipment which does not require large numbers of balance-of-system components and does not have a lot of National Electrical Code compliance issues.

Subtask 4.3 - Develop initial design

This milestone was completed in March of 1997 by Bill Hoffer.

Bill’s efforts have been concentrated on the prototyping of a modular enclosure system which allows the integration of multiple inverters, all of the required balance of systems components and sealed or non-sealed storage batteries. The goals are greater flexibility, lower cost and improved environmental tolerance (for outdoor mounting and tropical environments).

This approach was pursued after an evaluation of the 19” type rack mounting systems used in more typical commercial environments. The 19” type rack mounts were found to be expensive, not flexible enough and unable to allow the easy incorporation of the storage batteries. Most of the problems with 19” type rack mounts are due the greater weight of our inverter technologies and storage batteries.

A visit to a Denver area telecommunication battery supplier resulted in the development of a modular inverter / BOS / battery enclosure which can be configured in multiple configurations. This enclosure is designed for outdoor use or indoor use in difficult environments (such as tropical environments - bug proofing, etc.) The design is very similar to the systems used by manufactures of large UPS systems. The goal is to create a design which works for multiple inverter designs (the current SW and DR series and the 2-kW in development). The balance of systems capability is intended to handle systems up to 16.5-kW and includes all of the DC and AC disconnects, PV controllers, data acquisition components and even an area for a lap top computer either temporarily or permanently.

The Power Module enclosure system was designed to be stacked up to four high and to hold either one SW series inverter or two DR series inverters per enclosure. There is space for up to five C40 PV charge controllers per enclosure with all of the NEC required overcurrent protection and disconnect means. The Power Module enclosure system can also be used to hold a variety of sealed or unsealed battery types. Initially an indoor and an outdoor version was to be offered. Further discussions with industry determined that all versions should be outdoor capable.

Subtask 4.4 - Source components to implement design

The task was completed in March and April of 1997 to allow the prototype to be ready for the SOLAR 97 show in Washington, DC at the end of April.

The decision was made to go with a nearby metal fabricator who manufactures enclosures for the telecommunications industry. Some of their enclosures have been used in the PV industry, particularly for lighting systems. They also have done enclosures which includes power electronics, batteries and fuel powered back-up generators.

Most of the balance-of-system components needed to build up the prototype units are already purchased by Trace for other applications, except for the modular enclosure system.

Subtask 4.5 - Develop prototype of power module and rack system

The task was completed in March and April of 1997 to allow the prototype to be ready for the SOLAR 97 show in Washington, DC at the end of April.

Subtask 4.6 - Present mock-up to industry and collect feedback

This task was completed in April of 1997 by Bill Hoffer. The prototype Power Module enclosure / BOS system was displayed at Solar 97 conference in Washington, DC and the World Solar Conference in Barcelona, Spain in June of 1997.

Additional development occurred after the display of the prototypes at the conferences. The Power Module enclosure systems went into full production in November of 1997.

In January of 1997, the Power Module enclosure system was submitted to UL for listing as a Photovoltaic accessory under UL1741. The evaluation was completed in March of 1998. The first UL listed Power Module enclosures were displayed at the SOLTECH / UPVG conference in Orlando, Florida at the end of April, 1998.

Subtask 4.7 - Complete report on packaging system

This report was provided as part of the Final Review Meeting held at NREL on June 25, 1998. (D-2.8)

5.0 PROGRAM PLAN

This development program proceeded on schedule over the course of the first year. The change in the selected topology and the development of the commercially promising CO-sine inverter product did delay the schedule slightly.

Near the end of the Phase I program, Milt Rice, the primary design engineer, was killed in an airplane crash. This significantly delayed the completion of several of the final milestones as noted in the following sections.

5.1 Schedule

With the loss of Milt the schedule was pushed back approximately 4 months while we regrouped and made the required personnel changes. Work on the development of the control and protection system of the Phase II tasks was continued by Greg Thomas using the existing SW series as a modular inverter platform. This allowed progress to be made on the modular inverter protection, control algorithms to allow paralleling on the modular inverters and the further optimization of the additional protection circuitry.

An engineering lab technician was assigned the task of duplicating the existing hybrid modular inverter prototype and then completing preliminary tests on the two units to ensure that the performance could be duplicated and that the existing schematics and documentation were correct. One of the prototypes was than sent to another Trace engineer, Mike Frost, for additional testing, evaluation and development.

5.2 Milestones

PHASE I MILESTONES

M - 1.1.1 Complete definition of the topology for the 2-kW prototype inverter

This milestone was completed twice during the development process - once for the high frequency inverter design and once for the hybrid inverter design. The further development of the high frequency inverter into the CO-sine derivative product was completed outside of this contract.

M - 1.2.1 Complete design of the 2-kW prototype inverter

This milestone was reached in April of 1996 with the completion of the prototype breadboard construction of the hybrid inverter design. This prototype was then revised to allow incorporation of the components in the existing DR series inverter chassis.

M - 1.3.1 Complete 2-kW inverter prototype for performance testing

This milestone was reached in June of 1996 with the construction of the hybrid inverter design using the existing DR series inverter chassis.

M - 1.3.2 Complete successful operation of a prototype

This milestone was reached in June of 1996 with the successful operation of the hybrid inverter design.

M - 1.3.3 Complete initial testing of the 2-kW inverter

This milestone was reached in June of 1996 with the successful operation and the initial evaluation of the hybrid design. Additional testing was completed on various circuits intended to reduce the no load power consumption.

M - 1.3.4 Complete Task 1

This milestone to provide inverter topology design and verification of operation was reached in June of 1996. The result of this task was to design and prototype the construction of the 2-kW modular inverter for utility interactive and remote power applications.

M - 1.4.1 Complete Problem Identification and Development of Solutions

This milestone was reached in July of 1996 with the development of the low idle power consumption method and the advanced protection system for the inverter's MOSFET transistors.

M - 1.4.2 Complete revision of the prototype

This milestone was reached in July of 1996 with the development of the low idle power consumption method and the advanced protection system.

M - 1.4.3 Complete performance verification of the revised prototype

This milestone was reached in August of 1996 with the further development of the low idle power consumption method and revisions to the transformer design to allow higher power and improved efficiency.

Demonstration of the prototype for utility connected and stand-alone applications as well as bi-directional ability was completed. The design was determined to be compatible with the control methods used to control the SW series inverter/charger for these application.

M - 1.4.4 Complete Task 2

This milestone to optimize the performance was reached in August of 1996 with the completion of the idle power consumption circuit development, prototype optimization, inverter protection circuit development, active current limiting system and additional testing.

PHASE II MILESTONES

M - 2.5.1 Complete definition and detailed requirements for the control and protection systems

This milestone was completed in January of 1997 by Greg Thomas and Christopher Freitas. A report of the requirements was completed and delivered at the Final Review Meeting held at NREL on June 25, 1998.

M - 2.5.2 Complete hardware requirements to implement control and protection of the modular inverter system

This milestone was completed in two steps. The first step was the addition of the DC-side protection circuit for the MOSFET bridges. The development of this protection circuit was completed in February of 1997 and it was put into production on the SW series inverters in April of 1997.

A hardware solution was also developed in October of 1997 which solved the issue of the inverters fighting each other when lightly loaded. This solution was fielded in November of 1997 on the first paralleled inverter systems at three sites in Australia using pairs of SW4548A inverters.

M - 2.6.1 Complete software requirements to implement control and protection of the modular inverter system in intended applications

This milestone was completed in January of 1997 initially. Additional software development was completed as issues and solutions were found.

M - 2.6.2 Complete selection of devices to implement control and protection of the modular inverter system

This milestone was completed in October of 1997 and the first paralleled inverters were fielded using the developed hardware and software in November of 1997 in three systems for Australia. Two additional systems were also completed and shipped to Hong Kong and to South America.

M - 2.6.3 Complete prototype of the control and protection design

This milestone was completed in October of 1997 and the first paralleled inverters were fielded using the developed hardware and software in November of 1997 in three systems for Australia. Two additional systems were also completed and shipped to Hong Kong and to South America.

M - 2.6.4 Complete the definition for the packaging requirements

This milestone was completed by Bill Hoffer during the period of January to March of 1997. A report was delivered as part of the Final Review Meeting held at NREL on June 25, 1998.

M - 2.6.5 Complete the investigation of industry packaging designs

This milestone was completed in January of 1997. The result was the decision to build a custom enclosure instead of using existing 19”rack mount type systems. This is due to the greater requirement for handling heavy weight items (such as batteries, inverters and transformers) and the use of large diameter cables. The 19” rack mount systems are also designed for equipment which does not require large numbers of balance-of-system components and does not have a lot of National Electrical Code compliance issues.

M - 2.7.1 Complete initial designs of the packaging system

This milestone was completed in March of 1997 by Bill Hoffer.

M - 2.7.2 Complete sourcing components for prototype of packaging system

This milestone was completed in April of 1997 by Bill Hoffer. The prototype Power Module enclosure / BOS system was displayed at Solar 97 conference in Washington, DC and the World Solar Conference in Barcelona, Spain in June of 1997.

M - 2.7.3 Complete development of prototype packaging system

This milestone was completed in April of 1997 by Bill Hoffer. The prototype Power Module enclosure / BOS system was displayed at Solar 97 conference in Washington, DC and the World Solar Conference in Barcelona, Spain in June of 1997. Additional development occurred after the display of the prototypes at the conferences. The Power Module enclosure systems went into full production in November of 1997.

In January of 1997, the Power Module enclosure system was submitted to UL for listing as a Photovoltaic accessory under UL1741. The evaluation was completed in March of 1998. The first UL listed Power Module enclosure systems were displayed at the SOLTECH / UPVG conference in Orlando, Florida at the end of April, 1998.

M - 2.8.4 Present prototype of packaging system to industry

This milestone was completed in April of 1997 by Bill Hoffer. The prototype Power Module enclosure / BOS system was displayed at Solar 97 conference in Washington, DC and the World Solar Conference in Barcelona, Spain in June of 1997.

M - 2.8.5 Complete report on packaging system design

This milestone was completed June of 1998. A report was delivered as part of the Final Review Meeting held at NREL on June 25, 1998.

M - 2.8.6 Complete task 3

This milestone was completed June of 1998. A report was delivered as part of the Final Review Meeting held at NREL on June 25, 1998.

M - 2.8.7 Complete task 4

This milestone was completed June of 1998. A report was delivered as part of the Final Review Meeting held at NREL on June 25, 1998.

M - 2.8.1 Complete test and evaluation of parallel and series operation of the modular inverter concept

This milestone was completed in March of 1998. A report was delivered as part of the Final Review Meeting held at NREL on June 25, 1998.

M - 2.8.2 Complete refined prototype control and safety systems

This milestone was completed in April of 1997 by Greg Thomas. The final version was put into production on all the SW series inverter in April and on the DR series starting in May of 1997.

M - 2.8.3 Complete report on performance levels achieved and identify areas needing work or improvement

This milestone was completed June of 1998. A report was delivered as part of the Final Review Meeting held at NREL on June 25, 1998.

6.0 DELIVERABLES

6.1 Reports

PHASE I REPORTS

D - 1.1 Report Summarizing Performance of Initial Prototype Inverter

A report summarizing the results of the testing was provided in February of 1997.

D - 1.1 Report Summarizing Performance of Revised Prototype Inverter

A report summarizing the results of the testing was provided in February of 1997.

PHASE II REPORTS

D - 2.1 Report defining requirements for the control and protection

This report was provided as part of the Final Review Meeting held at NREL on June 25, 1998.

D - 2.3 Report summarizing test results of the control and protection system using the current SW series inverter/charger product

This report was provided as part of the Final Review Meeting held at NREL on June 25, 1998.

D - 2.4 Report detailing packaging investigation

This report was provided as part of the Final Review Meeting held at NREL on June 25, 1998.

D - 2.6 Deliver prototype of modular 2-kW inverter fully capable of true parallel operation in modular packaging system

The prototype modular inverter system was shipped to the agreed upon test facility for final evaluation and testing.

D - 2.7 Final Task 3 control and protection report

This report was provided as part of the Final Review Meeting held at NREL on June 25, 1998.

D - 2.8 Final Task 4 packaging report

This report was provided as part of the Final Review Meeting held at NREL on June 25, 1998.

D - 2.9 Report summarizing the test results for the modular inverter design

This report was provided as part of the Final Review Meeting held at NREL on June 25, 1998.

D - 2.10 Report detailing the suitability of the control and protection system and the packaging system on other inverter topologies

This report was provided as part of the Final Review Meeting held at NREL on June 25, 1998.

6.2 Presentations and Publications

- A presentation was made at the NREL / Sandia Photovoltaic Program Review Meeting in November 1996 by Christopher Freitas.
- The “Power Module” modular packaging system was presented to the PV industry at the SOLAR 97 conference at Washington, DC in April of 1997.
- The “Power Module” modular packaging system was also presented to the PV industry at the World Solar in Barcelona, Spain in June of 1997.
- A presentation was made on July 16th , 1997 at the SERF center at NREL on the work being completed under the PVMaT contract.
- The Power Module enclosure system brochure was developed and released to the PV industry at several shows.
- The Power Module enclosure system was advertised in several trade journals.

7.0 GLOSSARY OF TERMS

AC	Alternating current type electricity as supplied by a utility grid
Balance-of-systems	All of the additional equipment required for a system other than the inverter, batteries and PV modules
DC	Direct current type electricity as supplied by batteries or PV modules
H-Bridge	A type of transistor switch arrangement which allows the DC electricity to be converted to AC electricity
Hot swap	To change a modular inverter without shutting down the system
Inverter	A device which converts DC to AC type electricity
Inverter Module	A complete inverter designed to operate either on its own or as part of a system with other inverter modules to power AC loads from a DC source
MOSFET	A type of transistor often used in low voltage DC power electronics. Stands for Metal Oxide Silicon Field Effect Transistor
Power Module	This product incorporates the inverter and the balance of systems components (cables, breakers, controllers, metering etc.) into a single outdoor, bug proof metal enclosure

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13. ABSTRACT *(Maximum 200 words)*
This research and development contract has resulted in several benefits for Trace Engineering and the PV industry that are directly attributable to the PVMaT program:

- Application of the hardware based protection circuit developed in Phase I was completed on Trace's existing DR and SW series product lines. This additional protection circuit was phased into full production starting in April of 1997. This resulted in a substantial improvement in factory yields and a very significant reduction of field failures – a drop of as much as 80% on some product models.
- Accelerated development and introduction of the Power Module enclosure/balance of systems package. This product is a big step towards the standardization of system and equipment design for Trace's customers.
- Developed the cost reduced 2.5-kW modular inverter based on the current SW series software and topology. This new inverter/charger uses many new construction and manufacturing methods to reduce cost by 40% , simplify production, decrease parts count by over 20%, reduce labor required by 30% , and increase the flexibility in the manufacturing process. It will enter production in the first quarter of 1999 as the Trace Engineering PS series inverter/charger.

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